An Assessment of the Capabilities of the ERS Satellites' Active Microwave Instruments for Monitoring Soil Moisture Change

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Abstract

The launch of the European Remote sensing Satellite (ERS-1) in July 1991 represented an important turning point in the development of Earth observation as it was the first of a series of satellites which would carry high resolution active microwave (radar) sensors which could operate through the thickest cloudcover and provide continuity of data for at least a decade. This was of particular relevance to hydrological applications, such as soil moisture monitoring, which generally require frequent satellite observations to monitor changes in state. ERS-1 and its successor ERS-2 carry the active microwave instrument (AMI) which operates in 3 modes (synthetic aperture radar, wind scatterometer and wave scatterometer) together with the radar altimeter which may all be useful for the observation of soil moisture. This paper assesses the utility of these sensors through a comprehensive review of work in this field. Two approaches to soil moisture retrieval are identified: 1) inversion modelling, where the physical effects of vegetation and soil roughness on radar backscatter are quantified through the use of multi-frequency and/or multi-polarization sensors and 2) change detection where these effects are normalized through frequent satellite observation, the residual effects being attributed to short-term changes in soil moisture. Both approaches will be better supported by the future European Envisat-1 satellite which will provide both multi-polarization SAR and low resolution products which should facilitate more frequent temporal observation.

Introduction

The hydrological cycle is one of the main systems by which energy is redistributed on a global scale and a better understanding of its functioning over a range of scales is required to enable global circulation models to be parameterized more accurately. Energy exchange occurs whenever there is a movement of water: it occurs within the atmosphere as a result of evaporation and rainfall, at the land surface when runoff occurs as streams and rivers or within the soil and deeper aquifers as a result of gravity, evaporation or mechanical abstraction. Soil moisture plays a key role in the hydrological cycle as, along with snow, surface water and groundwater, it is one of the variable storage terms which reflect global changes in water mass balance. In addition, soil moisture exerts an important control on the transfer of energy and water at the land surface where, for most parts of the Earth, the availability of soil moisture determines the rate of evaporation, as well as controlling the development of vegetation. Evaporation and transpiration are the main sources of atmospheric water and the associated latent and sensible heat fluxes provide much of the energy to drive climate dynamics. The surface soil layer is where the largest changes in moisture take place and this strongly influences energy exchange. This is also the region which is observed by remote sensing, so the potential for monitoring soil moisture fluxes on a global scale is real, but there are many factors which must be taken into account before this can be realized. The challenge is to make best use of existing satellite sensors for advancing knowledge of surface soil moisture distribution and its changes over a range of scales, whilst using this knowledge to define future satellite systems to carry out the task more accurately and efficiently.

The Active Microwave Instruments on ERS-1/2

The Active Microwave Instrument (AMI) on the European Space Agency ERS-1 satellite was the first satellite instrument to provide radar data worldwide for long-term Earth observation. As early as 1978, the US SEASAT satellite provided a unique foretaste of the possible applications of satellite SAR; unfortunately, it failed after only 3 months' successful operation (Allan, 1983). ERS-1 has now been superseded by ERS-2, which was launched in April 1995, followed by other satellites carrying radar such as the Canadian Radarsat (launched November 1995) and the European Envisat-1 (planned launch around 2000) which together will provide continuity of data well into the next century.

The AMI operates in 3 modes, all at C-band (5.3GHz) VV polarization and these are described in detail in Vass and Battrick (1992, pp. 23–29). The synthetic aperture radar (SAR) image mode provides high resolution (around 25m) images of size 100 × 100km and is the most widely used for soil moisture applications. The SAR wave mode provides similar data to the image mode, but in smaller 5 × 5 km 'imagettes' which are spaced at 200 or 300 km intervals. This mode is intended primarily for sampling ocean wave spectra and could be used over land, but no reports of its use for soil moisture studies have yet been found. The Wind Scatterometer is characterized by its ability to measure backscattering coefficients in three azimuthal directions (forward 45°, across track, backwards 45°), which results in two different incidence angles and a ground resolution of 50 km. Such data are therefore suitable only for studies over large areas where seasonal changes in soil moisture, vegetation and roughness are of interest.

The other active microwave instrument on ERS-1 is the radar altimeter which operates at Ku-band (13.8 GHz) and is nadir pointing with a footprint of 16–20 km (Vass and Battrick, 1992, pp. 33–37). Although not well suited to the measurement of soil moisture, reports of it responding to soil moisture variability have been made.

Microwave radar has a number of advantages over conventional sensors for the assessment of soil moisture. Not only has it the ability to acquire data at frequent and predictable intervals thanks to its penetration of cloud, but there is also, at microwave frequencies, a direct physical link, via the soil dielectric, between soil moisture and radar backscatter. This relationship is essentially independent of ambient conditions such as temperature and sun angle which, at higher frequencies, require the effects of soil moisture to be inferred. However, with radar, other factors, such as radar incidence angle, surface roughness and vegetation effects, must either be quantified or minimized before the soil moisture effects can be isolated.

Theoretical background to soil moisture measurement

The most important factors that determine the radar backscattering from soils are the geometric properties (slope and surface roughness) and the electrical properties. The dielectric properties are defined by the dielectric constant, which has a strong influence on the backscatter. The dielectric constant, ε, is a complex parameter (also known as the complex permittivity) consisting of a real component, ε', the permittivity of the material, and a much smaller imaginary component, ε'', the dielectric loss factor:

$$\varepsilon = \varepsilon' - \varepsilon''$$

At C-band (5.3GHz), dry soil has a permittivity (ε') of about 3 whilst water has a permittivity of about 80 (Ulaby *et al.*, 1986, pp. 2086–2104). When these two materials are mixed, the resulting dielectric constant can range from 3 (for completely dry soil) to over 25 (for wet soil) as shown in Fig. 1. It can also be seen that radar sensitivity to soil moisture change is greatest at the lower frequencies around 1.4–6 GHz (L–C-band), whilst

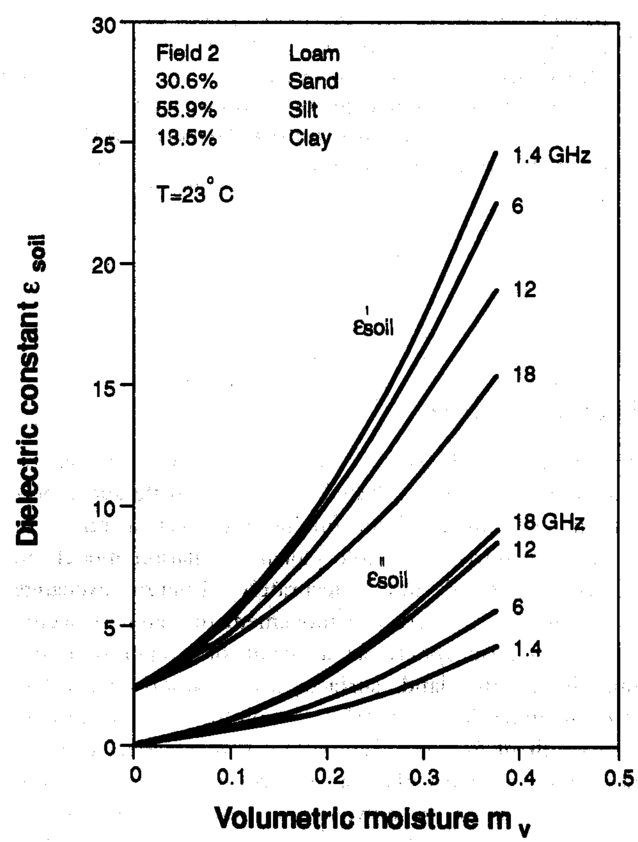

Fig. 1 *Measured dielectric constant (ε' real, ε'' imaginary) as a function of volumetric moisture content for a loamy soil at 4 microwave frequencies (after Ulaby et al., 1986, p 2096)*

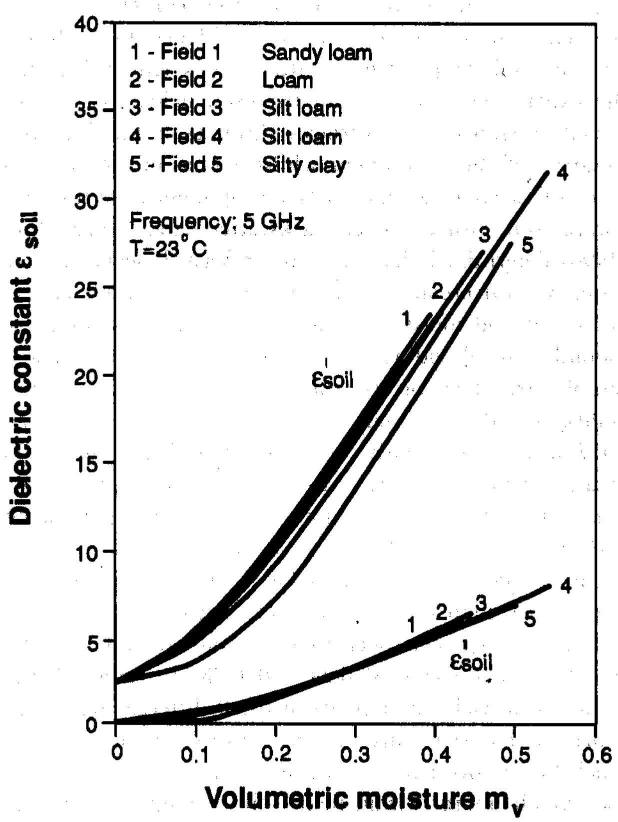

Fig. 2 *Measured dielectric constant (ε′ real, ε″ imaginary) for five soils at 5GHz and incidence angle 23°. (after Ulaby* et al. *1986, p. 2092)*

Fig. 2 shows that, for a given radar frequency, the relationship of dielectric constant to soil moisture is also dependent on soil texture which must be accounted for when comparing different soil types. Because microwave radar frequencies only interact with the top layer of soil, typically the top 2 cm at C-band, (Ulaby *et al.*, 1982, page 852) the determination and modelling of surface/profile soil moisture relationships are generally employed to help infer soil moisture state within the root zone from satellite microwave measurements (e.g. Ragab, 1995)

There are two fundamental approaches to radar measurement of soil moisture as described by Carver (1987). The first uses instantaneous estimation of absolute near-surface soil moisture by employing physically-based models of radar/surface interaction and the second relies on change detection procedures to estimate increments (or decrements) of near-surface soil moisture.

The accuracy of the first approach is constrained by the ability to correct the estimated volumetric soil moisture, m_v, for the effects of unwanted 'target noise' on the radar backscatter coefficient (σ^0) as a function of sensor resolution. The main sources of 'target noise' when esimating soil moisture are: 1) vegetation effects, 2) surface roughness effects and 3) surface slope effects and the following simplified model can be applied :

$$\sigma_T^0 = \sigma_V^0 + \frac{\sigma_S^0}{L^2}$$

where σ_T^0, σ_V^0, σ_S^0, and L^2 are, respectively, the total backscatter observed by SAR (at some frequency, polarization, and angle of incidence), the backscatter contribution from vegetation, the backscatter contribution from the soil, and the two-way attenuation loss due to the canopy. The dependence of σ_S^0 on volumetric moisture is given by:

$$\sigma_S^0 = R\alpha m_v$$

where R is a surface roughness coefficient and α is a soil moisture coefficient. Both R and α vary in an approximately known fashion as functions of radar frequency, polarization, and incidence angle. Because they are dependent upon local angle of incidence, they are sensitive to local slope.

By combining Equations 1 and 2 and solving for m_v:

$$m_v = \frac{L^2}{\alpha R}(\sigma_T^0 - \sigma_V^0)$$

Ulaby *et al.* (1986, pp. 1936–1941) showed, both by theoretical calculation and by ground-based scatterometer experiments, that radar sensor configuration could be optimized for the measurement of soil moisture. The sensitivity to soil moisture could be maximized by careful selection of radar frequency, polarization and incidence angle, whilst the effects of vegetation and surface roughness could be reduced. The optimum radar configuration was found to be at frequencies of 4–5 GHz with incidence angles between 7 and 22 degrees. The most suitable polarization may vary according to the vegetation and soil surface geometry and can only be defined with *a priori* knowledge of surface and vegetation conditions. Accordingly, the configuration of the ERS-1 SAR (5.3 GHz, VV polarization and 23 degrees incidence angle) is well suited to the monitoring of soil moisture.

The change detection approach looks for changes in radar backscatter in a time series of two or more SAR images. By observing at frequent time intervals (ideally 3 days or less), the effects of scene variables which tend to change slowly as a function of time (such as vegetation or surface roughness) are normalized, so that more rapidly changing variables such as soil moisture may be identified. This approach is made easier with ERS-1 data as a result of the very accurate location of one image relative to another and, for relatively flat areas, local radar incidence angle is essentially constant over time. In hilly regions, intra-scene dislocation becomes more important and geometric correction of the data using digital terrain models may become necessary. In both cases, the assumption is that surface slope is constant, whilst surface roughness changes abruptly only as a consequence of tillage. The seasonal backscatter characteristics of vegetation vary greatly according to type; sometimes they display distinctive phases of rapid change but there are also periods when little change is evident. Thus, the timing of data acquisition can be critical if the change detection method is to succeed over crops.

Achievements with ERS-1 SAR data

Soil moisture studies using ERS-1 AMI data are regarded, worldwide, as being of crucial importance to the better understanding of water and energy fluxes occurring at the land/atmosphere interface. Measurement of soil moisture changes over time and space are required at the local scale for agricultural and river catchment applications and at the regional or mesoscale for ecological, hydrological and energy budget models; these, in turn, will enable scaling up to the ultimate requirement of global energy and moisture circulation models. ERS-1 and 2 have for the first time enabled soil moisture effects to be studied over extended periods (in excess of 5 years at the time of writing) covering a wide range of climates, soil types and vegetation covers, to provide a unique source of data for comparative studies. Such a wide range of independent studies enables both problem areas and successful applications to be identified more accurately with the aim of developing better and more widely applicable soil moisture retrieval models.

Because the effects of soil moisture and vegetation on radar backscatter are inexorably linked, many studies have included soil moisture measurement either as a primary requirement, such as for hydrological applications, or as a secondary, perhaps unwanted, variable, such as for land use applications. All of the results indicate that soil moisture within the top few centimetres has a significant effect on backscatter recorded by the ERS SAR and scatterometer and by the radar altimeter. This is a significant finding, as all 3 sensors operate at different incidence angles; 23°, 18–59° and 0° respectively. However, the majority of studies have used the SAR mode because its high spatial resolution (around 25m) enables validation sites of field size to be located.

BARE SOIL SITES

To eliminate the effects of vegetation on radar backscatter, a number of studies included the use of bare soil sites. Wooding *et al.* (1993) and later Griffiths and Wooding (1996) describe a soil moisture study on sandy loam sites in southern England where 18 SAR PRI images were acquired during the ERS-1 3-day repeat Commissioning Phase between July and December 1991. The work was linked to radar calibration activities requiring the deployment of calibrated corner reflectors; this ensured a high degree of confidence in both the absolute and temporal backscatter values acquired during the experiment. Three main bare soil fields were maintained as smooth, flat surfaces throughout the 5 month duration of the experiment whilst a total of 23 bare soil fields of varying size and surface roughness were used for comparison with extracted backscatter data. Fellah *et al.* (1996) determined that fields of at least 3 hectares were required to overcome the effects of image speckle and to determine soil moisture with a measurement accuracy of around 5%. Wooding *et al.* (1993) determined that a sample size of 60 pixels (approx.1ha) would give a variability of the estimate of backscatter smaller than ±0.25dB; consequently, the selected fields were all greater than 1 hectare with most being considerably larger than this. Fig. 3a shows the relationship between ERS-1 SAR backscatter and 0–5 cm soil moisture for the 3 smooth fields. Bare soil fields 1 and 3 have, respectively, very high correlations coefficients (*r*) of 0.98 and 0.99 and good sensitivity to soil moisture indicated by the slope coefficients of 0.24 and 0.38. Virtually all the variation in backscatter between the 9 different dates was explained by variations in soil moisture. Field 2 had a much lower correlation coefficient *r* and sensitivity; there was much more within-field soil variability than the others and its surface roughness changed during the duration of the experiment.

By measuring the bare soil backscatter for a range of roughnesses on both dry and wet days, Wooding *et al.* (1993) established that the effect of temporal variations in soil moisture (approx. 7dB) for any given field was at least of equal magnitude to the effects of changing surface roughness (approx. 5.5dB). This supports the theory that, at high angles of incidence, the effects of surface roughness are minimized (Ulaby *et al.*, 1982, pp. 827–828). The effects of surface roughness on backscatter remained the same over the whole moisture range (approx. 10–40% by volume) experienced during the experimental period, suggesting that any changes between surface and volume scattering which might be expected as the soil dries out were minimal (*cf.* Kerr and Magagi, 1994, as referred to in the Wind Scatterometer section). However, the effects of roughness variations must be quantified in any backscatter model used to predict soil moisture, especially where directional biases are present as a result of tillage (Michelson, 1994).

Poncet *et al.* (1994), working on bare sandy loam to sand soils in Brandenburg, obtained correlation coefficients *r*, up to 0.84 and slope coefficients of 0.57 when relating 0–10 cm soil moisture (mean value between surface and 10cm depth) to radar backscatter over a soil moisture range of 9–24% by volume. An attempt was made to obtain inter-field estimates of soil moisture variation through correlation of small polygons of 8-30 pixels with soil moisture transect measurements,

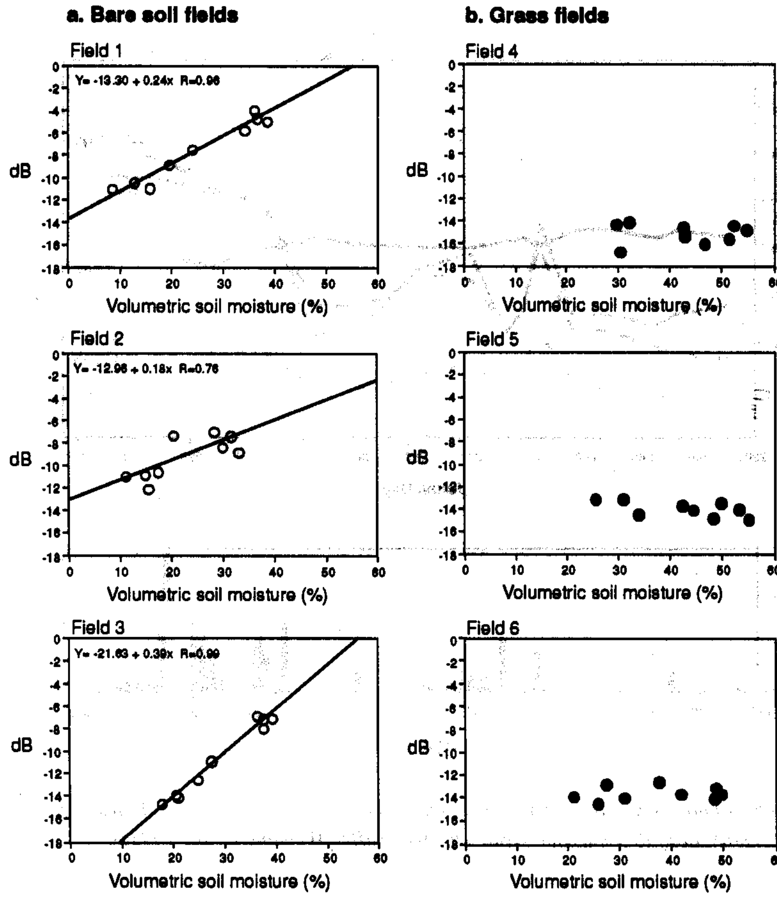

Fig. 3 *Relationship between mean ERS-1 backscatter (dB) per field and 0–5 cm depth soil moisture (% by volume) for a) 3 smooth, bare soil fields and b) 3 grassland fields at Romney Marsh, U.K. (after Wooding et al. 1993)*

but results were poor. Venkataratnam *et al.* (1994) found that on typical semi-arid red and black soils near Hyderabad, higher correlation coefficients r of around 0.6 were obtained with soil moisture measurements made at 5–10 cm depth, compared to those at 0–2 cm or 2–5 cm depth. These differences were thought, by the authors, to have been due to surface roughness variations for which they had not fully accounted. Mohan *et al.* (1994), found that on alluvial soils in the Agra district of northern India, both 0–5 cm and 0–10 cm soil moisture measurements gave similar correlations with radar backscatter. A wide range of soil moisture was experienced from 1 to 30% by weight and, across about 60 bare soil sites, very strong correlations of soil moisture and radar backscatter were obtained in the presence of rms (root mean square) roughness height variations of 0.68 cm to 2.1 cm.

GRASSLAND SITES

The possibility of estimating soil moisture over bare soil sites has been well demonstrated but, in many parts of the world, especially in temperate climates, bare soil is present only for a short period between crop harvest and the emergence of the following year's crop. Soil moisture information is required throughout the year and it has been suggested that grazed pasture would be a suitable reference surface as a result of its presence throughout the year, its lack of tillage resulting in relatively stable roughness and the generally small vegetation effect as a result of grazing (Blyth and Andrews, 1990). Bijker and Hoekman (1994) were able to differentiate 'class 1' pastures in the Colombian Amazon basin from the other main land use types by identifying seasonal changes in backscatter of the 51 sample sites resulting from grazing, recuperation of the grass, shrub invasion, shrub cleaning, burning and changes in soil moisture condition. In their initial studies of U.K. grassland, Blyth *et al.* (1994) found good soil moisture/backscatter correlation for sheep-grazed pasture on sandy soils. Further studies generally confirmed these findings but the results obtained on heavier clay soils showed no correlation, even in the presence of an almost unchanging, short sheep-grazed vegetation cover (Blyth, 1994). Wooding *et al.* (1993) also found no correlation for 3 sheep-grazed pasture fields on sandy soils for data collected on 9 overpass days (Fig. 3b). However, on taking the mean backscatter

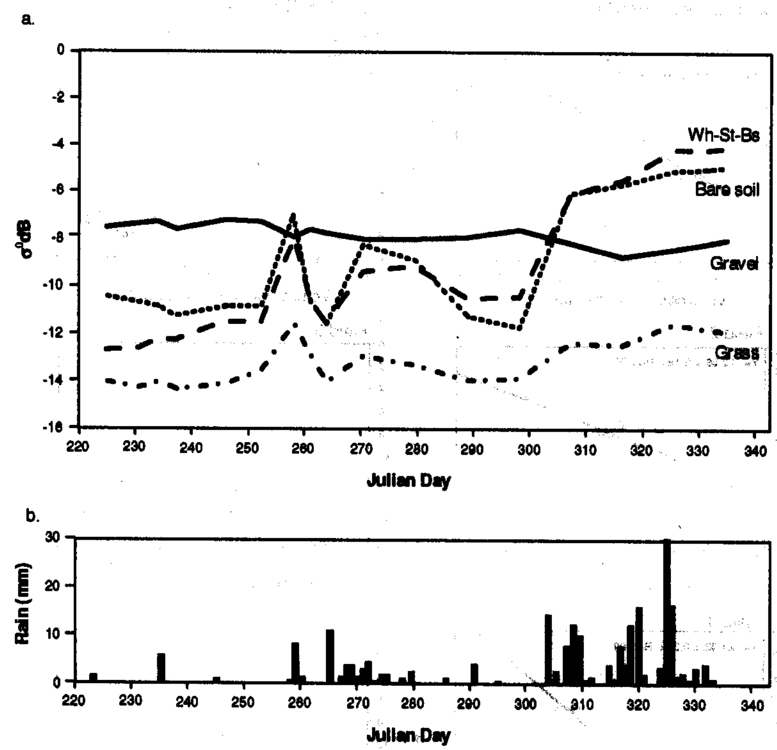

Fig. 4 *(a) Temporal changes in radar backscatter (dB) for 4 land cover types: 1. Gravel, 2. Wheat stubble with bare soil (Wh-St-Bs), 3. Bare soil and 4. Grass. (b) Daily rainfall (mm) for Lydd-On-Sea. (after Wooding et al., 1993)*

values for 60 grassland fields, acquired from 18 ERS-1 overpasses over a 4 month period, he found that grassland did respond to rainfall in a similar way to bare soil and cereal fields (Fig. 4), but its sensitivity range was only about 2.7dB compared to the bare soil range of about 6.7dB. The results of Cognard *et al.* (1995) are described more fully in the following section but, for grassland sites, only weak positive correlations of surface soil moisture with radar backscattering coefficient were found. Fellah *et al.* (1994) reported a significant increase in radar backscatter of around 2.5dB for both grassland and cultivated soils following rainfall events in the 4–14 mm range. Dabrowska-Zielinska *et al.* (1994) reported mixed results over grassland in Poland. When data from 5 SAR passes were analysed (some of which were from different SAR frames), a relatively poor 0–10 cm soil moisture/backscatter correlation of 0.53 was found. When only 2 passes of the same SAR frame were used, the correlation improved to 0.72 over a soil moisture range of 10–75% by volume which resulted in a backscatter range of −13.5 to −9.5dB. Dobson *et al.* (1992) applied simple vegetation and roughness models, using field data collected over hayfields and prairie grass in north Michigan, to produce simulated ERS-1 SAR backscatter values. In all cases, the simulated and actual results agreed to within 0.4dB and they concluded that 'the retrieval of soil moisture from ERS-1 SAR is certainly feasible for surfaces covered with low biomass such as short grassland. The results also indicate that the quantity of biomass can lead to significant estimation errors (if not accounted for) as biomass approaches and exceeds 1 kg m^{-2}'. Wang *et al.* (1994) used the Santa Barbara microwave canopy backscatter model to compare modelled with actual backscatter observations over short grass fields and young loblolly pine forest. They found that, when the soil was wet (near field capacity), the backscatter from the short grass fields was greater than that from the pine stands and radar backscatter for the grass fields increased by about 5dB in the transition from dry to wet soils.

The results over grassland are, thus, conflicting and this probably reflects the wide range of grassland sward quality and structure encountered and their effects when combined with soils of different texture and bulk density. Established swards have a very dense surface root structure which essentially forms an organic mat over the soil which may account for the insensitivity of some results to surface soil moisture changes. Poorly maintained grassland often retains a considerable amount of dead vegetation within its understorey; this can have a similar masking effect, as found by Martin *et al.* (1989) during soil moisture validation of C-band scatterometer data over burned and unburned tallgrass prairie. Newly reseeded pastures will not have developed such a structure and can be expected to behave more like bare soil when the vegetation is closely grazed. The application of simple models to account for different vegetation and surface roughness states (e.g. Saatchi *et al.*, 1994) would appear to be necessary to help reduce ambiguities in these data.

CULTIVATED SITES

Given the sometimes conflicting results obtained over grassland sites, it is perhaps surprising to report on the sensitivity of the ERS-1 SAR to surface soil moisture changes beneath crops. Rombach *et al.* (1994) used 2, single look complex (SLC) images of the Freiburg test area acquired during the Commissioning Phase to monitor soil moisture under 3 corn (maize) fields, 3 harvested barley fields and 1 fallow field, all on loamy to gravelly sand with low clay content. The corn crop was at its maximum height of 200–250 cm for the whole observation period, and on maturing, showed a green leaf area index reduction from 4 to 0 which was not readily discernible in the backscatter data. On correlating backscatter with 0–5 cm soil moisture, all but 2 data points lay within the 5% confidence limits and a correlation of 0.89 was obtained. It was felt that soil moisture accuracies of ± 5% by volume were required for meaningful input to hydrological models, representing for the flat field case a SAR calibration accuracy of better than 0.5dB. This was felt to have been achieved and improved methods of soil moisture validation were considered necessary to match the sensitivity of the ERS-1 SAR instrument. The study was extended later to include 28 SAR scenes; Mauser *et al.* (1994) were able to produce a 0–5 cm depth reference surface soil moisture map by separating the effects of vegetation and soils and subsequently normalising all the data against a reference field of corn on a sandy loam soil. The resulting field-by-field map showed greatest spatial variability in August when the contrast between dry barley fields, intermediate corn field and moist irrigated corn could be identified. In September, the influence of underlying soil type was most evident with the heavier loam/clay soils appearing moister than the lighter sand/sandy loam soils. By November, this difference had disappeared as all soils approached field capacity and evapotranspiration effects were minimized. Differences due to land use and irrigation practices could no longer be detected. The results of this study appeared sensible for the Freiburg test site, but have to be tested for transportability to different vegetation and soil types.

Mohan *et al.* (1994) carried out measurements on bare soil as described earlier and also on mustard crops at the flowering stage, of mean height around 115 cm and 80–90% ground cover. Little difference between the bare soil and mustard crops could be seen in terms of correlation coefficients and sensitivity. For the combined data set, the standard error of estimate was within 3% over the available dynamic range of –18 to +10dB. Venkataratnam *et al.* (1994) also compared bare soil conditions with a mixture of bare soil and crops, the latter producing better correlations (around 0.71 compared to 0.6 for bare soil) but displaying significantly less sensitivity to soil moisture variations. Dabrowska-Zielinska *et al.* (1994) obtained higher backscatter/soil moisture correlations under winter rye ($r = 0.74$) than on grasslands ($r = 0.53$). This was attributed to the much lower biomass of the winter rye which would allow penetration of the radar to the underlying soil. However, lower correlations were obtained with spring wheat. Wooding *et al.* (1994) found that, at times of complete crop cover, results relating winter wheat backscatter to surface soil moisture in East Anglia, U.K. were only weakly positive (r value not given); significant relationships were observed only on Boxworth sand and Feltwell peat whilst no relationship was found between backscatter and soil moisture for oil seed rape. However, he noted that 'at early and late periods during the growing season when the crop canopy is low, during crop senescence and after harvest, backscatter is again dominated by soil properties (surface roughness and moisture) and other agronomic variables'.

SIXED SITES AT RIVER BASIN SCALE

Cognard *et al.* (1995) carried out soil moisture validation measurements over a 2 year period within a 12 km^2 river catchment in central Brittany to compare with ERS-1 SAR backscatter. The Naizin experimental catchment was of mixed agriculture, predominantly cereals and grassland and 13 fields were selected where volumetric surface soil moisture was measured. Within one of these fields, soil moisture was also monitored automatically using dielectric probes to better observe temporal variations which were believed to be well representative of the basin as a whole. At the field scale, the effects of vegetation strongly affected the sensitivity of radar response to surface soil moisture. The correlation of soil moisture to radar backscatter was weak; the best correlation was obtained for cereals ($r = 0.44$) followed by corn ($r = 0.37$), grass ($r = 0.23$) and vegetables ($r = 0.17$). Of more interest for hydrological modelling was the ability to assess the 'hydric state' of the river catchment as a whole. To do so, the mean radar signal was calculated for the entire catchment and was compared to the mean surface soil moisture content using measurements from the 13 test fields. Although the linear correlation was meaningful ($r = 0.8$), the sensitivity was rather weak, probably as a result of the wide range of vegetation and surface roughness effects. On comparing the mean catchment backscatter with the automatically-recorded soil moisture, a clear linear correlation was observed for the autumn, winter and mid-spring periods, but this correlation was lost by the end of spring and during summer due to the development of denser vegetation canopies which prevent penetration of microwave energy to the soil surface. It should be noted that monitoring of soil moisture during winter will be affected during freezing conditions and this is discussed in the following section.

Later, Cognard *et al.* (1996) also report on the results of the ERS-1 phase D (3 day repeat) data acquisition. which resulted in a significant correlation (r = 0.92) between mean radar backscatter and point source automatic soil moisture measurements within the Naizin catchment. A simple two layer model was used to represent the soil surface and the root zone, whilst a vegetation index derived from NOAA/AVHRR images was used to partition evaporation and evapotranspiration. The model was calibrated over the Naizin catchment and was then applied to 30 other catchments in Brittany. The results of this extensive application broadly confirm those of the Naizin study and indicate that satellite radar acquired at 3 day intervals can provide quantitative information on basin-wide soil moisture during winter and spring during periods of low vegetation density and high soil moisture. This offers the possibility of incorporating radar data in hydrological models to improve streamflow forecasting during the wet winter period.

Fellah *et al.* (1996) analysed more than 20 springtime and autumnal ERS-1 images over an extensive area on the Alsace plain, France to determine the sensitivity of the ERS-1 SAR to surface soil moisture. Denser summer vegetation was found to reduce the radar sensitivity to soil moisture, but for a single overpass in April, antecedent rainfall was strongly correlated with radar backscatter (r = 0.943 for crops, r = 0.929 for grassland). The effects of radar speckle on backscatter variability were determined and it was concluded (as previously indicated) that a minimum area of around 3 hectares (or 300 pixels) was required to determine the backscatter coefficient to a measurement accuracy of 0.5dB in order to determine soil moisture to an accuracy of around 5%. Furthermore, a strong correlation was also found at the regional scale where the effect of different land use types was averaged.

EFFECTS OF SURFACE FREEZING ON SOIL MOISTURE OBSERVATION

It has been shown that winter observations of soil moisture are likely to benefit from reduced vegetation cover, but the effects of freezing of the soil surface must be taken into account. Table 1 shows typical dielectric values which may be observed at C-band. Air is taken as unity and the permittivities of the other substances are expressed relatively. Wet soil may have a relative permittivity of around 25 which will produce high surface backscatter at temperatures above freezing, but this will be reduced to around 3 (mixture of dry soil and ice) at and below 0 °C. This effect was observed by Morrisey *et al.* (1996) in their study of Alaskan Arctic tundra. During the winter when all areas were frozen, wetland regions could not be distinguished from non-wetlands. For wetland regions, backscatter reductions between 2.8 and 4.1dB (decibels) were observed in summer ERS-1 images due to the effect of freezing. These effects enabled the main methane source areas to be distinguished and a methodology derived for long-term monitoring of these climatologically sensitive areas.

Table 1. **Approximate relative permittivity of natural substances at microwave frequencies**

Medium	Relative Permittivity (ε')
Air	1
Water	80
Soil (dry)	3
Soil (wet)	25
Ice	3

Pulliainen *et al.* (1996) report similar reductions in backscatter of 3–4dB at C-band as a result of soil freezing in boreal forests in Finland. The collection of 23 ERS-1 SAR images enabled seasonal changes to be observed at the Porvoo test area between June 1993 and March 1994. Their results confirm the findings of Morrissey *et al.* (1996) that greatest scene information is acquired during the early thaw period when the contrast between frozen and unfrozen ground is most evident. In order to interpret the data correctly, local meteorological information is essential whilst the combination of morning descending and night-time ascending node images may be advantageous to study the effects of diurnal temperature change.

French *et al.* (1996) also used ERS-1 to study soil moisture variability in boreal forest in Alaska. Measurements of soil water following forest fires were required to understand post-fire ecology and its recovery. An increase in soil water content at the surface typically follows fire, particularly in areas with underlying permafrost, because of the melting of frozen soil and the reduction in evaporation. At each of a range of fire-burned sites, 30–40 soil samples were collected and generally high gravimetric values were recorded (~ 0.8 to 3.3 g water/g soil). Results indicated that a positive linear relation (r = 0.79) exists between soil water content and SAR backscatter in young burns (< ~ 4 years). Older burns did not show this relationship as a result of vegetation establishment following the burn which masked the soil signal. It was concluded that the use of this information from ERS-1 SAR would help in the estimation of variables such as carbon dioxide and trace gas fluxes from boreal forest ecosystems.

Modelling and soil moisture retrieval

It is clear from the above examples that soil moisture has a significant effect on ERS-1 SAR backscatter both under bare soil conditions and when vegetation with a low moisture content is present. Change detection techniques (Engman, 1991, Rignot and van Zyl, 1993) which may reduce the effects of surface roughness and vegetation to allow soil moisture retrieval, are likely to be most successful at the dry end of the soil and vegetation moisture spectrum and on sandier soils as predicted by radar theory (Ulaby *et al.*, 1986). Change detection requires that two or more SAR scenes are acquired in a time frame within which no significant change in the unwanted variables would be expected. Thus, with weekly SAR coverage, changes in vegetation and soil roughness would be minimal (except for obvious cropping or tillage), leaving soil moisture as the main source of change. These methods have produced very useful results in India and are likely to be applicable to many drier climates where moisture levels are of critical importance for agro-hydrological applications. For large area studies, where there is currently no proven procedure for obtaining details of surface roughness etc., change detection techniques are the only option. Villasenor *et al.* (1993) used both subtraction and ratio change detection techniques on 3 day repeat ERS-1 SAR of the North Slope of Alaska to identify the most significant sources of temporal change. Analysis of the difference images, together with climatological and hydrological validation data, showed that the backscatter changes were largely due to changes in soil and vegetation liquid water content induced by freeze/thaw events. A correlation with topography was found in the difference images which arose from the dependence of vegetation, organic layer thickness and volumetric water content on hillslope position and orientation. The conclusion was that, although image subtraction produced acceptable results, image ratioing was statistically more robust. Morrissey *et al.* (1996) used 24 ERS-1 images to study the temporal dynamics of arctic tundra and he was able to differentiate moist sites with characteristically low backscatter (–14dB ±0.3 S.E.), wet sites which exhibited the strongest returns (–9.5dB ± 0.1 S.E.) and saturated sites which exhibited intermediate backscatter (–1.9dB ± 0.4 S.E.).

In wet climates where soils at or near saturation are common, the sensitivity of radar backscatter to soil moisture reduces and vegetation moisture content increases dramatically. Under such conditions the retrieval of soil moisture becomes more difficult and modelling procedures become more important to account for changing surface roughness and vegetation effects. Le Toan *et al.* (1994) used the Integral Equation Model (Fung *et al.* 1992) to handle a range of slopes and roughnesses normally encountered in agricultural situations. Knowledge of both surface rms height (standard deviation of soil surface height) *s*, and correlation length (a measure of

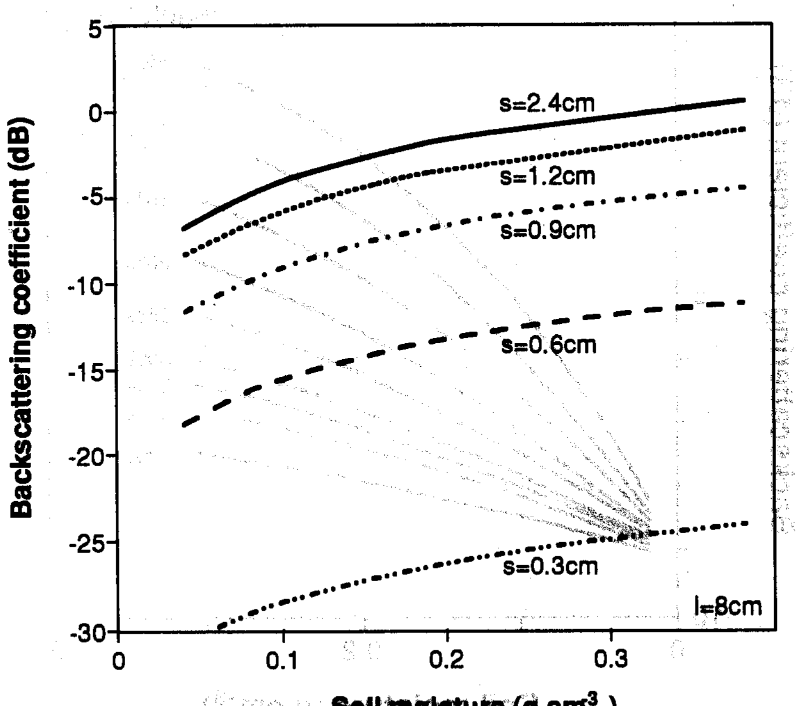

Fig. 5 *Simulation of backscatter coefficients as a function of surface root mean square height s at correlation length l = 8cm (after Le Toan et al., 1994)*

horizontal periodicity in surface height) l, were required to allow inversion of backscatter coefficient to soil moisture. Fig. 5 shows a simulation of backscattering coefficients as a function of surface rms height for a correlation length of 8 cm which is typical for agricultural soils. This simulation (Le Toan, *et al.*, 1994) shows that the sensitivity of radar backscatter is slightly more linear for smooth surfaces, with small increases in roughness producing marked increases in backscatter. This sensitivity to roughness reduces as surface rms height increases. Figure 6 shows the results of a vegetation simulation model run by Nghiem *et al.* (1993) for soybean for a radar operating at 5.3GHz, VV polarization and 20° incidence angle (very similar to ERS-1). The validated model has been used to simulate the backscatter coefficient responses to both the vegetation volume fraction and the soil moisture content. It can be seen that the sensitivity of radar backscatter to soil moisture decreases with increasing vegetation cover. It was found that the soil moisture can be related to backscatter if the vegetation volume fraction is low (< 0.1% for the soybean canopy). Beyond this value, both the vegetation and soil contribute to the backscatter. When the vegetation cover is dense, only the vegetation contribution remains.

Wang *et al.* (1994) used the Santa Barbara microwave canopy backscatter model for continuous tree canopies (Fig. 7), on ERS-1 SAR data to separate the effects of tree canopy backscattering and those from the underlying soil and used short grassland fields as a reference soil surface. The model simulation demonstrated that, under dry soil conditions, the ERS-1 backscatter was sensitive to tree biomass over a limited range but, under wet soil conditions, the major contributor to the total backscatter changed from canopy volume scattering to soil surface scattering. In this case, the conclusion was that the strong sensitivity of the ERS-1 SAR to changes in soil moisture, resulting from the configuration of the sensor, made it an unsuitable choice for forest biomass monitoring. Boisvert *et al.* (1997) used two surface radar backscatter models to evaluate soil moisture stratification in a bare soil induced by irrigation and evaporation. The modelling approach was very detailed in order to reproduce the surface and volume scattering effects within the near surface soil layers and under different surface roughness conditions. This type of modelling is essential to understand fully the factors controlling radar backscatter and to identify the most important ones, but for widespread application, such models must be generalized without losing their physical basis.

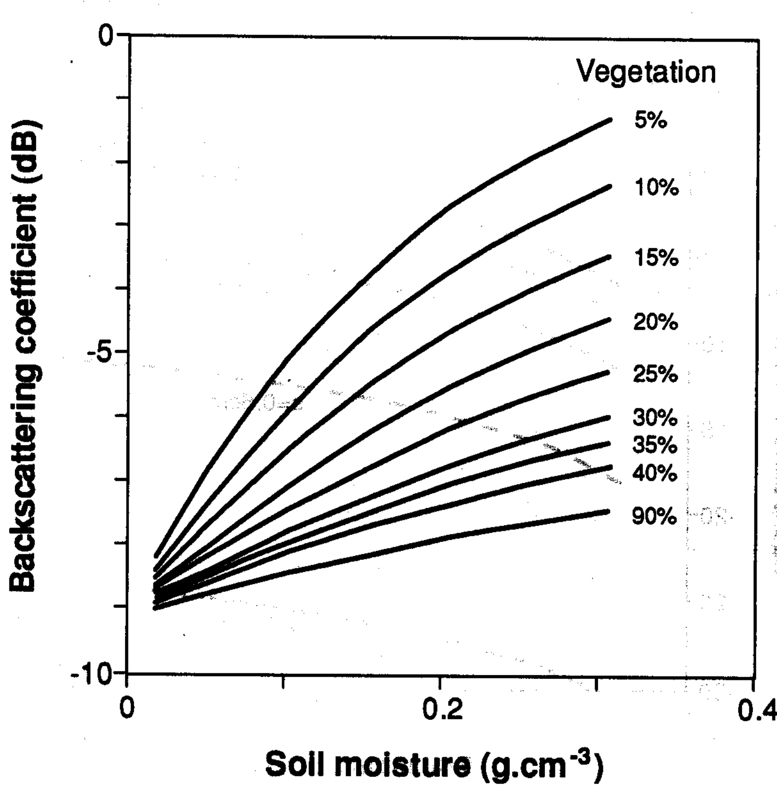

Fig. 6. *Simulation results showing the effect of the vegetation percentage cover on the relationship backscatter coefficient ($\sigma°$)/soil moisture (after Nghiem et al., 1993)*

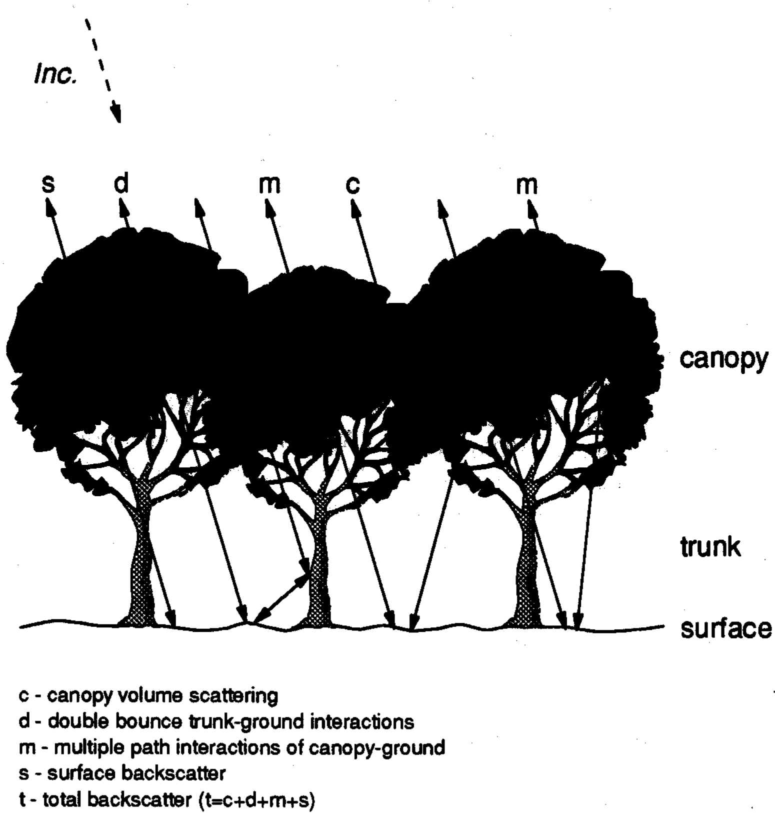

Fig. 7 *Santa Barbara microwave canopy backscatter model for continuous tree canopies. (after Sun, 1990)*

The inversion approach taken by Mauser *et al.* (1994) to map the spatial distribution of soil moisture using backscatter information was to normalize all the data to a reference surface for which all the necessary factors affecting radar backscatter had been measured. Crop, soil and roughness indices for fields within a 50 km^2 test area were stored within a GIS environment. The behaviour of the other surfaces relative to the reference surface (maize on sandy loam) was obtained through a statistical analysis of a time series of 28, 3-day repeat SAR images. 4 fields were selected to cover a combination of soil and crop types and these were instrumented to record, continuously, soil moisture at 4 depths, whilst vegetation parameters were measured weekly. This approach reduces the effort required for field validation, but is dependent upon a sufficiently large SAR data set fully to describe the effects on backscatter of different vegetation, soil, roughness etc. under the full range of soil moisture conditions. The relationships found in this study have not yet been proved to be stable or universal, so further work is required to determine their general applicability. The approach is, however, very attractive for future catchment-scale studies where extensive ground validation is not practicable.

Achievements with ERS-1 Wind-Scatterometer data

The Wind-Scatterometer was designed for use over the oceans and little was known about its likely performance over land. Its attraction for the estimation of surface soil moisture is its high temporal repetitivity of 4 days and its low spatial resolution of 50km which is well suited to the requirements of global modelling when supported by other higher resolution data (such as the ERS-1 SAR). It measures the backscattering coefficient in 3 azimuthal directions, corresponding to 2 incidence angles (Vass and Battrick, 1992, pp. 28–29). Consequently, it is possible to quantify 2 points of the backscattering coefficient as a function of view angle. The hypothesis put forward by Kerr and Magagi (1994) was that the slope of the function would be related to surface roughness, whilst the intercept would be linked mainly to vegetation biomass and soil moisture. For low incidence angles, backscatter is influenced largely by surface moisture, while for higher incidence angles the effects of vegetation are likely to predominate. Backscattering from soils is complicated by the fact that soils will either induce volume scattering (when very dry) or surface scattering (when moist) which will alter their interrelationship with soil roughness. Kerr and Magagi (1994) used the comprehensive ground validation data from the HAPEX-Sahel Experiment (Goutorbe *et al.*, 1994) to interpret wind-scatterometer data over the test area in Niger. Fig. 8 shows the seasonal evolution of soil moisture (0–5 cm) in relation to backscatter acquired for view angles between 18 and 21°. The two curves are very similar up to Julian day 242 (August 29) when the effects of vegetation development are becoming noticeable. These results are extremely encouraging and point to the need for further studies the better to isolate the effects of vegetation, surface roughness and soil moisture from the wind-scatterometer data and to test their utility over a range of climatic zones and vegetation types. Frison and Mougin (1996) also noted during their global vegetation studies of wind-scatterometer data that the evolution of the radar signal in semi-arid zones is at first related to an increase in soil moisture at the start of the growing season and is later influenced by the vegetation itself. Boreal regions comprising short vegetation (mainly lichens and mosses) also appeared to be responding to soil moisture changes and a marked reduction of backscatter was observed between June and September when drying of the vegetaion and soil would be expected. However, no validation measurements were available to support this theory. Wiesmann and Matzler (1994) found in their studies of the Central Plains of Switzerland that for mixed agricultural areas the highest backscatter values obtained with the 40° fore beam data corresponded to periods immediately following heavy rain and hence high soil moisture values.

A major problem with the wind-scatterometer data for soil moisture and related studies, which was expressed by Wiesmann and Matzler, was the reduced time resolution caused by the large time gaps in the data which made it impossible for them to monitor the real temporal changes of their test sites. For many soil moisture applications full data set repetitions would be ideally required every 2–3 days.

Achievements with Radar Altimeter and ATSR instruments

Whilst the ERS Along-Track Scanning Radiometer (ATSR) is not a microwave instrument, it is mentioned here for completeness as it is relevant to the study of soil moisture. Neither of these sensors can be considered of primary importance for soil moisture measurement but both may be used in a supporting role to provide additional information and perhaps to improve the temporal coverage of a region of interest.

The radar altimeter (Vass and Battrick, 1992, pp. 33–37) has a footprint of 16–20 km and operates at a higher frequency (13.8 GHz) than the other ERS microwave sensors. It could be used in conjunction with the wind-scatterometer to obtain additional angular information at low spatial resolution; its nadir look will be less sensitive to rough surfaces, whilst near specular reflection can be expected from smooth surfaces. Cudlip *et al.*(1994) suggested that, 'for smooth desert surfaces, wind-induced changes in surface roughness as small as

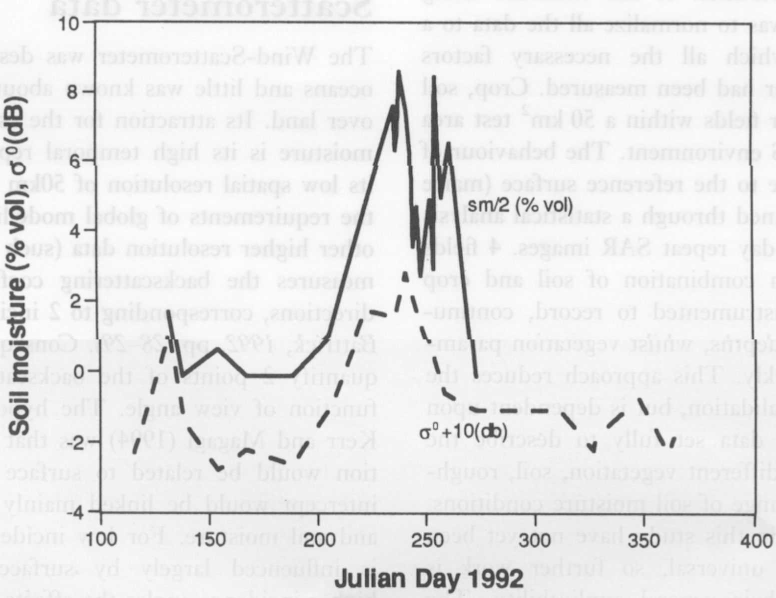

Fig. 8 *Comparative temporal evolution of 0-5cm soil moisture and backscatter coefficient (σ^o) acquired with wind-scatterometer mid-beam with view angle range 18–21°. Scaling factor: soil moisture is divided by 2 and σ^o is shifted by +10dB. (after Kerr and Magagi, 1994)*

3–10 mm may result in a persistent change in backscatter of up to 3 dB observed by the radar altimeter'. In addition, an increase in backscatter of around 3dB recorded by the altimeter over a large area in the southern Sahara was attributed to increased soil moisture from a large rainfall event.

The Along-Track Scanning Radiometer instrument (Vass and Battrick, 1992, pp. 41–46) provides thermal images of high radiometric resolution (around 0.2 °K) allowing the observation of small thermal gradients relating changes in soil moisture and soil texture, particularly in regions of sparse vegetation. The spatial resolution of the instrument is 1km which makes it more applicable to regional studies. Labed *et al.* (1994) using ATSR data in Niger, reported the ability to detect very subtle thermal structures which, in night-time images, related to paleodunes that affected the thermal and hydric properties of the area. Similarly, dark, elongated areas were found which corresponded to moist soil. This type of thermal information can potentially complement the data acquired with microwave instruments and may help determine regional estimates of soil moisture as detailed by Carlson (1986). Unlike microwave data, satellite thermal data are generally not suitable for monitoring soil moisture because of acquisition difficulties caused by cloudcover. However, they may be of value for the initialization or validation of various types of hydrological model as a result of the particular radiometric information they record.

Next Generation Satellites

Some of the requirements for taking soil moisture monitoring from the current development stage to operational applications will be aided by the next European microwave satellite 'Envisat-1' (Pfeiffer *et al.*,1993) which is planned for launch in 2000. Its advanced synthetic aperture radar (ASAR) will provide an alternating polarization mode (VV and HH) at 30m resolution which will help identify vegetation and soil roughness state at the field scale. The most important conclusion resulting from the NASA Shuttle SIR-C data collected over Holland was that 'crop classification with only one polarimetric image provides better results than with a time series of non-polarimetric images' (Netherlands Remote Sensing Board, 1995). In order to achieve more frequent repeat coverage than ERS, two low resolution products will be available; the wide swath mode providing 150 m resolution data and the global monitoring mode at 1000 m resolution which will cover the majority of the globe after 3 days and should facilitate repeat measurement every 3–7 days, depending on latitude. Both of these products will be available either at VV or HH polarization (Karnevi *et al.*, 1993). Whilst multi-frequency SAR would provide a better measure of roughness and vegetation effects, the cost and technical difficulties of providing such sensors on a single satellite are such that these are unlikely to be available within the next decade. However, the utility of multifrequency SAR has been demonstrated both through aircraft research programmes and through combination of satellite data of differing frequencies. Dobson *et al.* (1996) combined ERS-1 SAR: (C-band, VV polarization, 23° incidence angle) with the Japanese JERS-1 SAR (L-band, HH polarization, 35° incidence angle) and produced a knowledge-based conceptual model of vegetation/backscatter interaction to differentiate land use classes better than was possible from either sensor alone.

Conclusions

It is clear that the ERS-1 Active Microwave Instruments, the radar altimeter and the precise measurement of thermal emission with the Along-Track Scanning Radiometer, provide a powerful means of addressing the measurement of surface soil moisture over a wide range of scales. Most of the work undertaken so far has been 'proof-of-concept' in nature and has concentrated on local process studies, but future applications are likely to expand this knowledge to studies of larger areas.

Three main problems are evident which currently limit the utility of the ERS facility for soil moisture measurement. Firstly, the microwave energy interacts only with a thin top layer of soil (although the depth of this layer increases slightly with decreasing soil moisture) and for most hydrological applications, knowledge of water availability within the root zone is required. Modelling of surface/sub-surface soil moisture relationships such as undertaken by Ragab (1995), are required to be tested under a range of soil and vegetation conditions to enable spatial distributions of surface soil moisture derived from satellites to be incorporated more readily into hydrological models.

Secondly, the effects of surface roughness and vegetation cannot be determined directly with a single frequency, single polarization radar and future sensor improvements in this area are required. Currently, these effects are being quantified through the use of airborne multifrequency polarimetric radars (Held *et al.*, 1988) and controlled laboratory measurements (European Commission, 1995) which will help optimize the design of future satellite radars for soil moisture measurement. Dubois *et al.* (1995) have developed an empirical algorithm for the retrieval of soil moisture content and surface roughness using two co-polarized scatterometer channels and have tested the algorithm on airborne (AIRSAR) and spaceborne (SIR-C) data. Over bare soil and sparsely vegetated areas, soil moisture retrieval accuracies better than 5% were achieved and it is planned to extend the work to more heavily vegetated areas. This demonstrates the future potential of simple, dual polarization microwave sensing systems as planned for the European Envisat-1 satellite which should be operational at the turn of the century.

Thirdly, given the current limitations of single frequency, single polarization sensors, the favoured approach to soil moisture monitoring is through change detection. For change detection techniques to be successful, at least weekly repeat coverage is required to sample within the period of change of the unwanted variables, e.g. vegetation and roughness, and this is supported by the fact that the most useful data acquired on soil moisture using change detection was obtained during the 3-day repeat phases. As the 35-day repeat period selected for ERS-2 is probably the best compromise between global coverage and revisit time, the best option for future operational applications where high spatial resolution is required would appear to be the use of 2 or more satellites operating simultaneously. This option was partially tested during the simultaneous 'tandem' operation period of ERS-1 and ERS-2 when both satellites followed the same 35 day repeat ground tracks, with a separation in time of about one day. The 'tandem' mode was available for a period of 9 months (August 1995 to May 1996) and should provide improved knowledge of the spatial and temporal variability of surface soil moisture at test sites throughout the world. Further progress on soil moisture studies using ERS sensors will be reported at the 3rd ERS Symposium held in Florence in March 1997. Latest information on this symposium and other ERS related matters are available from the general web address: http://services.esrin.esa.it

The Canadian Radarsat satellite, which was launched in November 1995, can in theory provide repeat SAR coverage (C-band, HH polarization) over Europe every 2–6 days, depending on the operating swath width (ADRO, 1994) but this is achieved by changing the sensor look angle, the effects of which will have to be assessed carefully for soil moisture applications. Since commissioning of Radarsat was not completed until April 96, there has not been the opportunity to acquire Radarsat, ERS-1 and ERS-2 data at close time intervals as previously hoped; however, ERS-2 and Radarsat are planned to run in parallel for at least 3 years. This represents an important opportunity to study the dynamics of soil moisture and to develop techniques, probably in conjunction with microwave radiometer and thermal infrared data, for linking together spatial information on rainfall, soil moisture and evaporation into improved catchment water balance models.

Some of the most meaningful results for soil moisture monitoring have come from data sets collected during the ERS 3-day repeat periods and these point to the utility of future satellites providing similar repeat coverage. Positive results from both the ERS wind scatterometer and radar altimeter indicate that low resolution radar could be a way of achieving frequent temporal coverage for future operational applications and this type of data will be available in the near future through the Envisat-1 programme.

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